Improving the Design Process of the REgolith Imaging X-ray Spectrometer (REXIS) Using Model-Based Systems Engineering (MBSE)

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NASA GSFC Systems Engineering Seminar

Overview

- **Research Overview**
  - **Motivation**
  - **MBSE/SysML Introduction**
- Methodology
  - Metric Description
- REXIS Overview
  - Science Goals
  - Design History
- Case Studies
  - Interface Uncertainty Case Study
  - Design Consequence Case Study
- Conclusions

BLUF

Information extracted from system models can improve the efficiency of the design process

Research Motivation

Spacecraft frequently experience cost and schedule overruns

Complex spacecraft are more likely to fail or be impaired

Better systems engineering reduces cost/schedule overruns and manages complexity

Improving systems engineering in formulation will reduce cost/schedule overruns and enable more complex missions

Research Motivation

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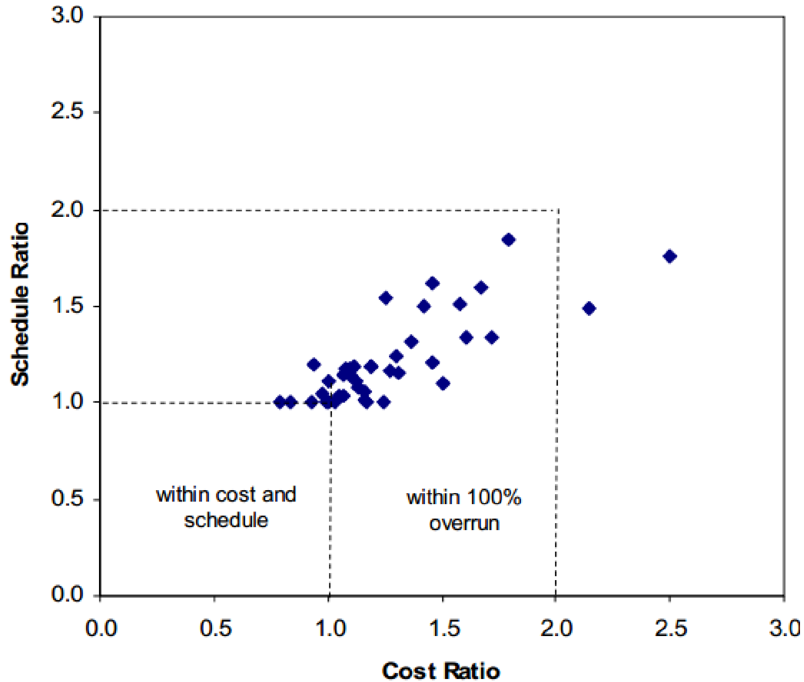
Cost and schedule overruns for selected NASA projects between 1992 and 2007. The average cost overrun is 27% and the average schedule overrun is 22% with cost and schedule overruns being correlated [1].

[1] D.L. Emmons, M. Lobbia, T. Radcliffe, and R.E. Bitten. Affordability Assessments to Support Strategic Planning and Decisions at NASA. In Aerospace Conference, 2010 IEEE, 2010.



Improving systems engineering in formulation will reduce cost/schedule overruns and enable more complex missions

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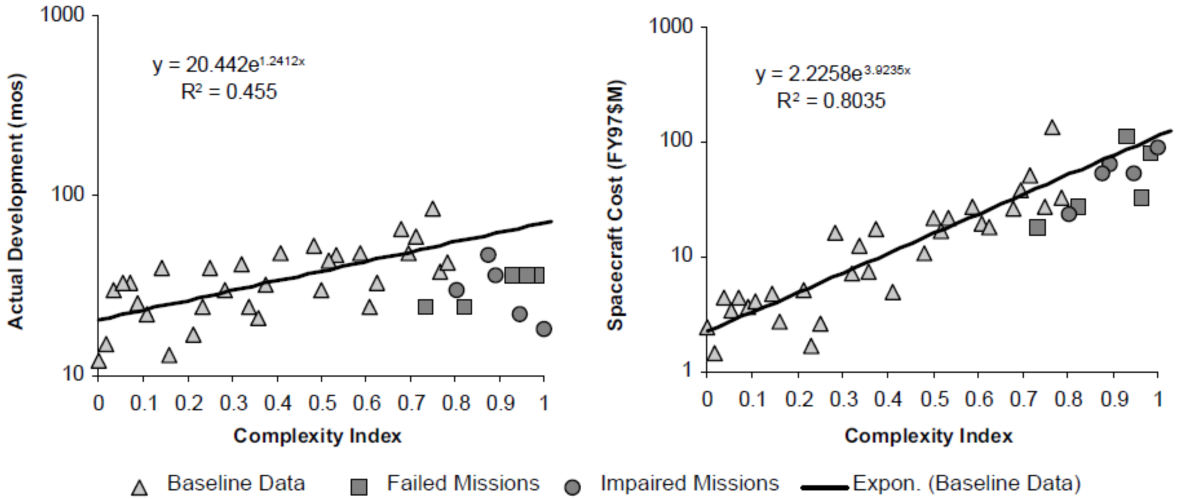

Failed and impaired missions tend to be more complex than average, yet have shorter schedules and tighter budgets than typical of project of their complexity [2].

[2] D.A. Bearden. A complexity-based risk assessment of low-cost planetary missions: when is a mission too fast and too cheap? Acta Astronautica, 52(26):371 - 379, 2003.

Improving systems engineering in formulation will reduce cost/schedule overruns and enable more complex missions

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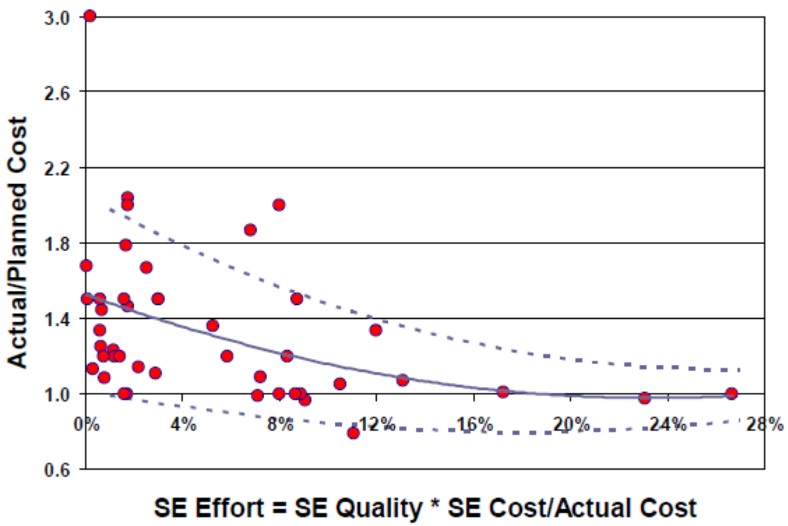
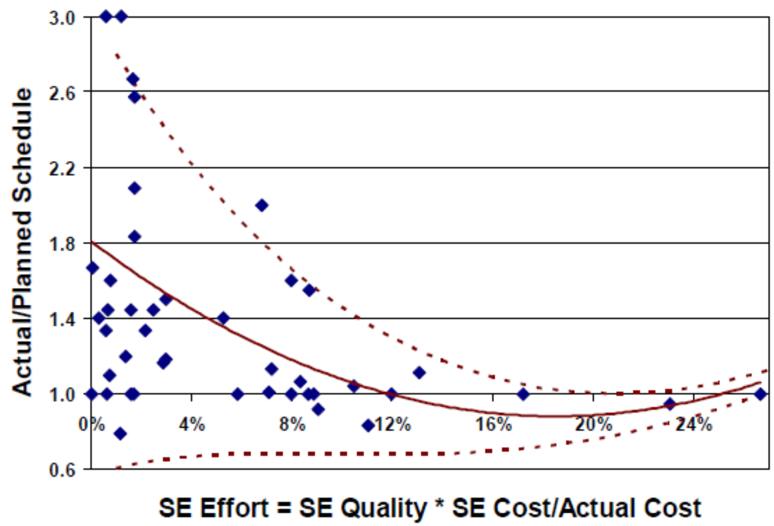




Increased systems engineering effort can decrease cost overruns and schedule overruns.
The dashed lines represent the 90% confidence bounds [3].

[3] E.C. Honour. Understanding the Value of Systems Engineering. In Proceedings of the INCOSE International Symposium, pages 1-16, 2004.

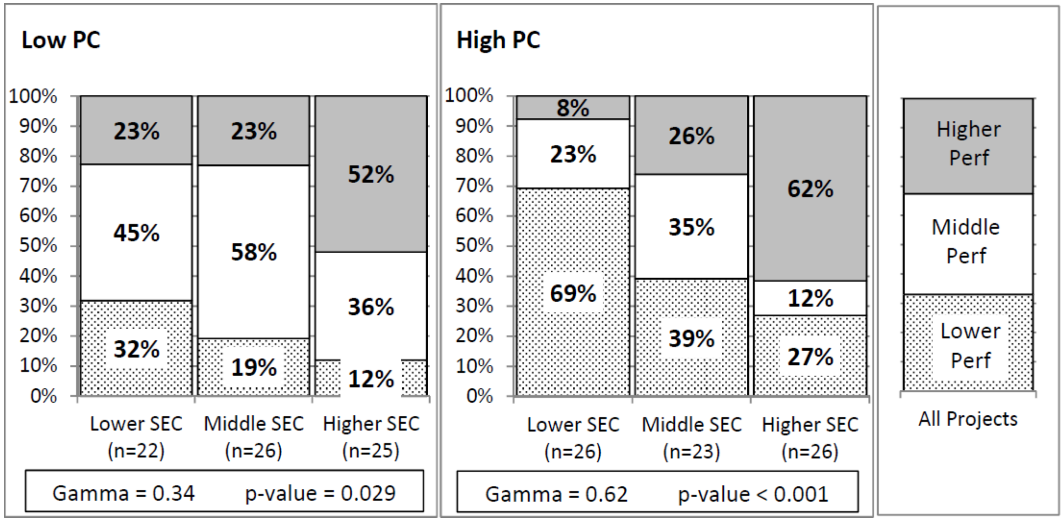
Improving systems engineering in formulation will reduce cost/schedule overruns and enable more complex missions

Research Motivation

Spacecraft frequently experience cost and schedule overruns

Complex spacecraft are more likely to fail or be impaired

Better systems engineering reduces cost/schedule overruns and manages complexity



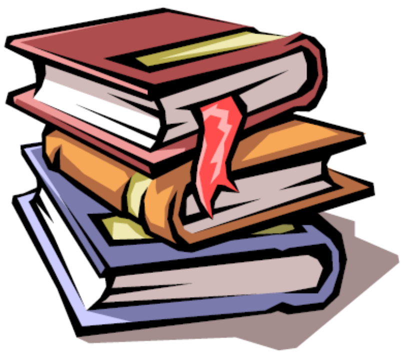
Increased systems engineering capabilities results in better performance. The effect in higher challenge projects is even stronger [4].

[4] Joseph P Elm and Dennis Goldenson. The Business Case for Systems Engineering Study: Results of the Systems Engineering Effectiveness Survey. Technical report, Carnegie Mellon University, 2012.

Improving systems engineering in formulation will reduce cost/schedule overruns and enable more complex missions

Model-Based Systems Engineering

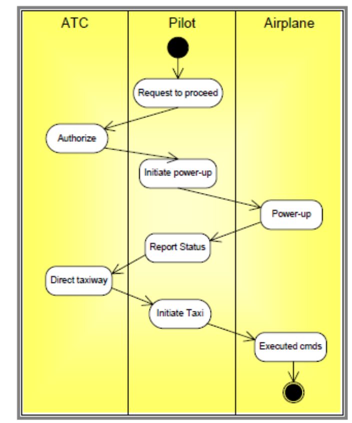
Past



SE Artifacts

- Specifications
- Interface requirements
- System design
- Analysis & Trade-off
- Test plans

Future

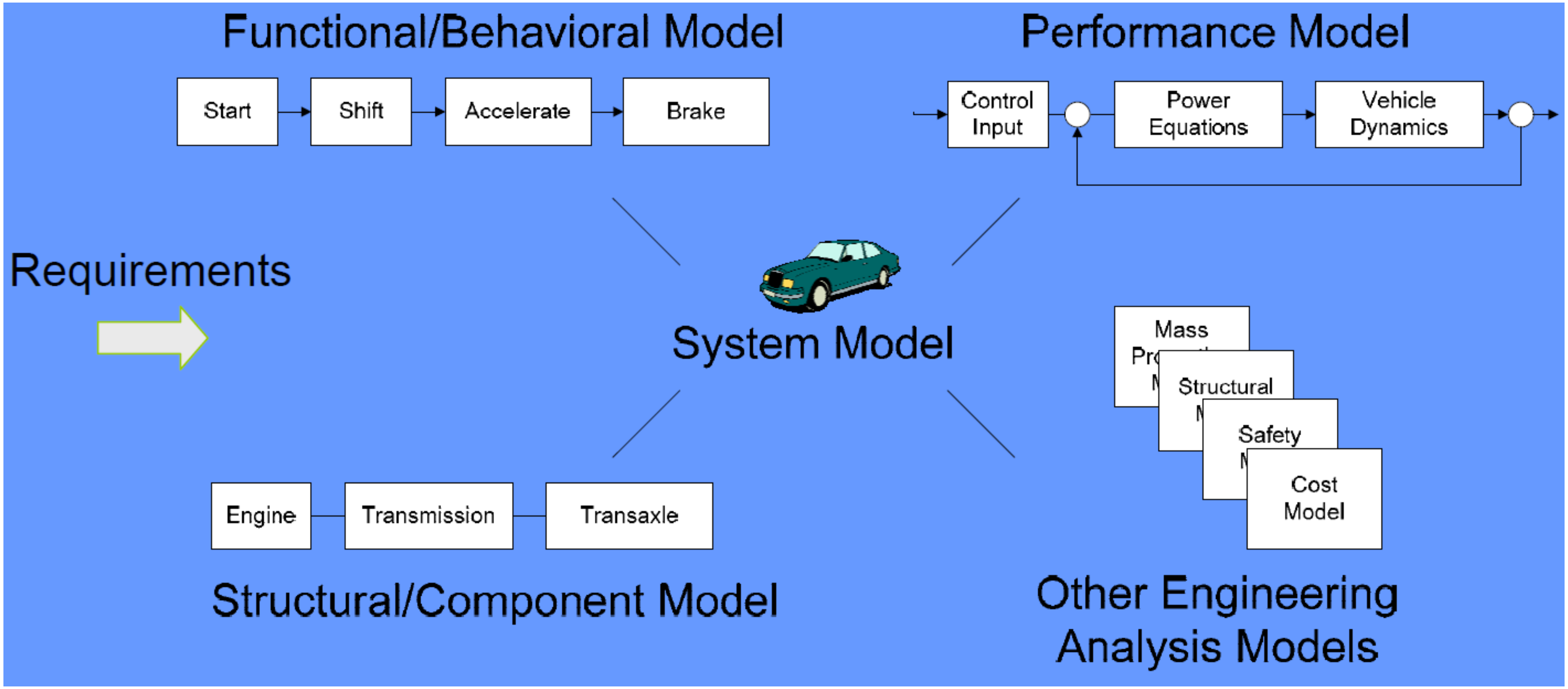


Document centric

Model centric

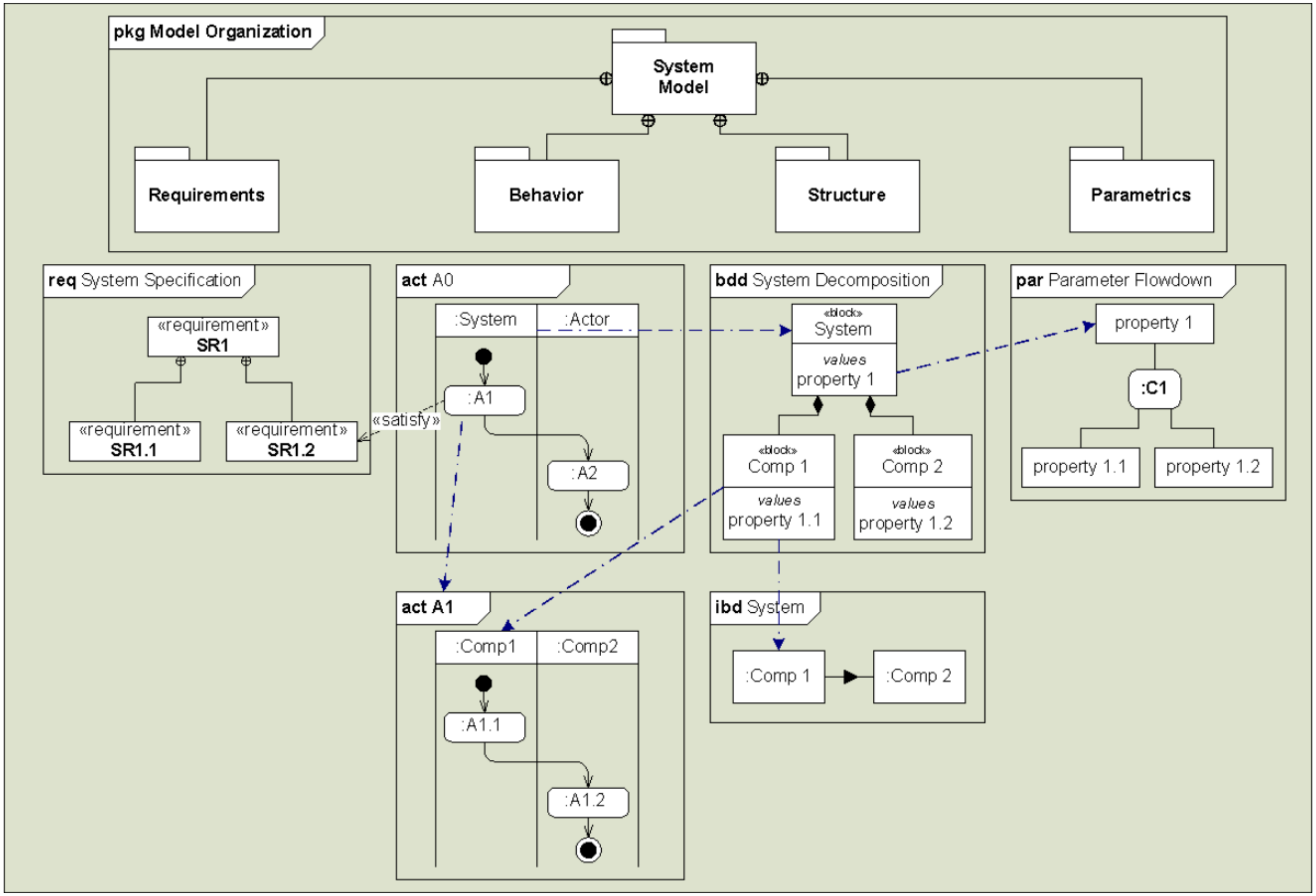
Descriptive models, instead of documents, are the information storage and communication medium [8]

MBSE System Model Scope



System model must capture information about all aspects of system [8].

The Systems Modeling Language



SysML diagrams capture different types of system information. Diagrams can be linked together [10].

Applications of SysML

- Requirements engineering
  - Implement requirements as constraints on the model, instead of as text statements within the model [11]
- System Description
  - Using SysML allows study of more mission concepts within the same timeframe [12]
- Integration with Analysis Tools
  - Graph transformations to support dynamic analysis in Simscape™ [13]
  - Integration with Phoenix ModelCenter® allows analysis in a range of tools [14]

Previous Research

- Design can be thought of as a series of decisions and MBSE can improve decision making [5,6]
- Detecting places where future changes will take place improves system development [7]
- MBSE allows greater insight into the system under development [8]
  - System topology currently not well captured

The topological information captured in a system model can assist in decision making and illuminate areas of future change

Research Hypothesis

Hypothesis

Implementing model-based systems engineering will improve the design process

Research Objective

To determine if implementing model-based systems engineering results in a more efficient design process

By comparing a hypothetical REXIS design process incorporating information from system models against the historical REXIS design process

Methodology

- Model the REXIS design at each design milestones in SysML
- Inspect the SysML models to extract information that was not known at the time and can improve the design process
- Measure how the information extracted from the model improves the design process

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Methodology

Create SysML models of design at points in design history

↓

Inspect models to extract information that is helpful to the design process

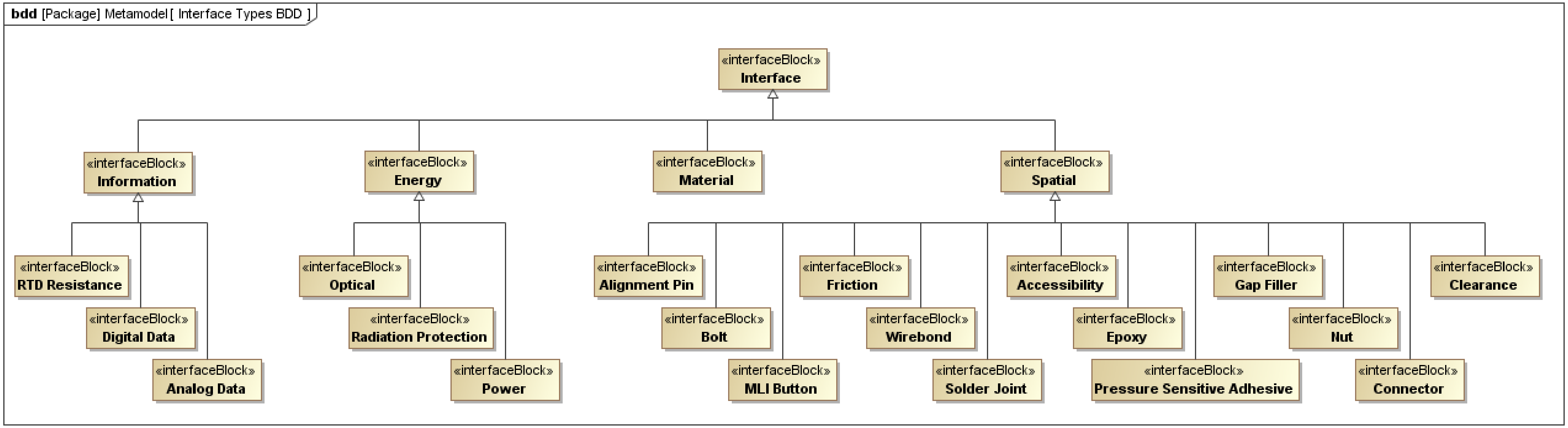
↓

Measure how the new information can improve the design process

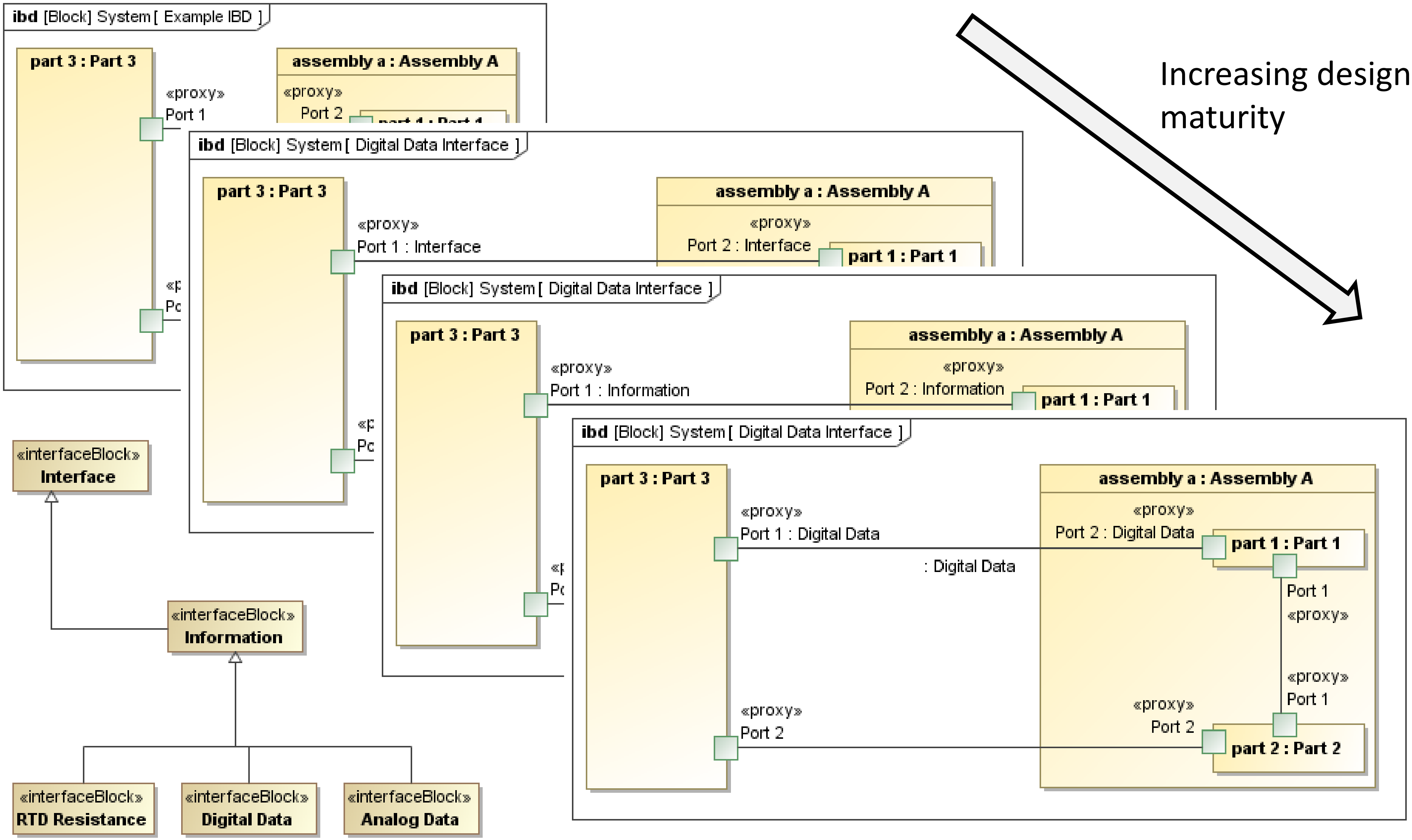
- System models contain topological information about the system
  - Interfaces
  - Interface uncertainty
    - Custom SysML extension
  - Design consequences
    - Custom SysML extension

Interface Uncertainty

- Knowledge about an interface at a point in time lies in an abstraction hierarchy
- More abstract interfaces are more uncertain
- All interfaces must be at the lowest level of abstraction in a finalized design
  - Interfaces with abstraction must change
- Modeled in SysML as an abstraction hierarchy of interface blocks and association blocks

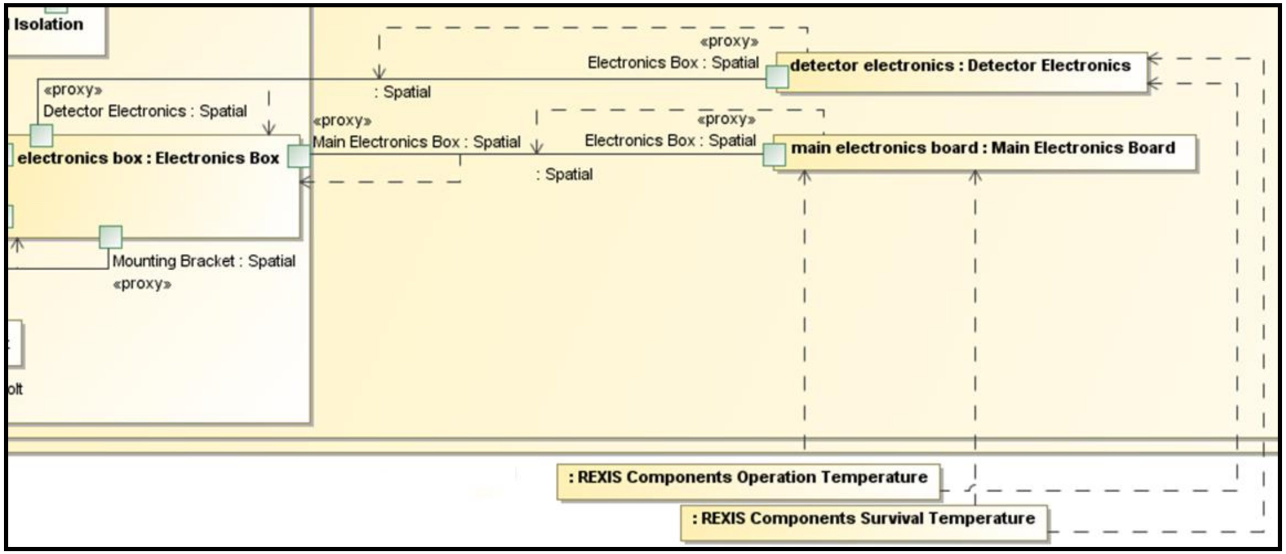


Interface Uncertainty Example



Design Consequence

- Captures how the ramifications of requirements or design decisions flow through the system
- A requirement or design decision may result in:
  - Components being added/removed
  - Changes in properties of existing components
- Tracing design consequence reveals how each requirement and design decision impacts the system
- Modeled in SysML using Dependencies that flow from the source requirement or design decision through the system



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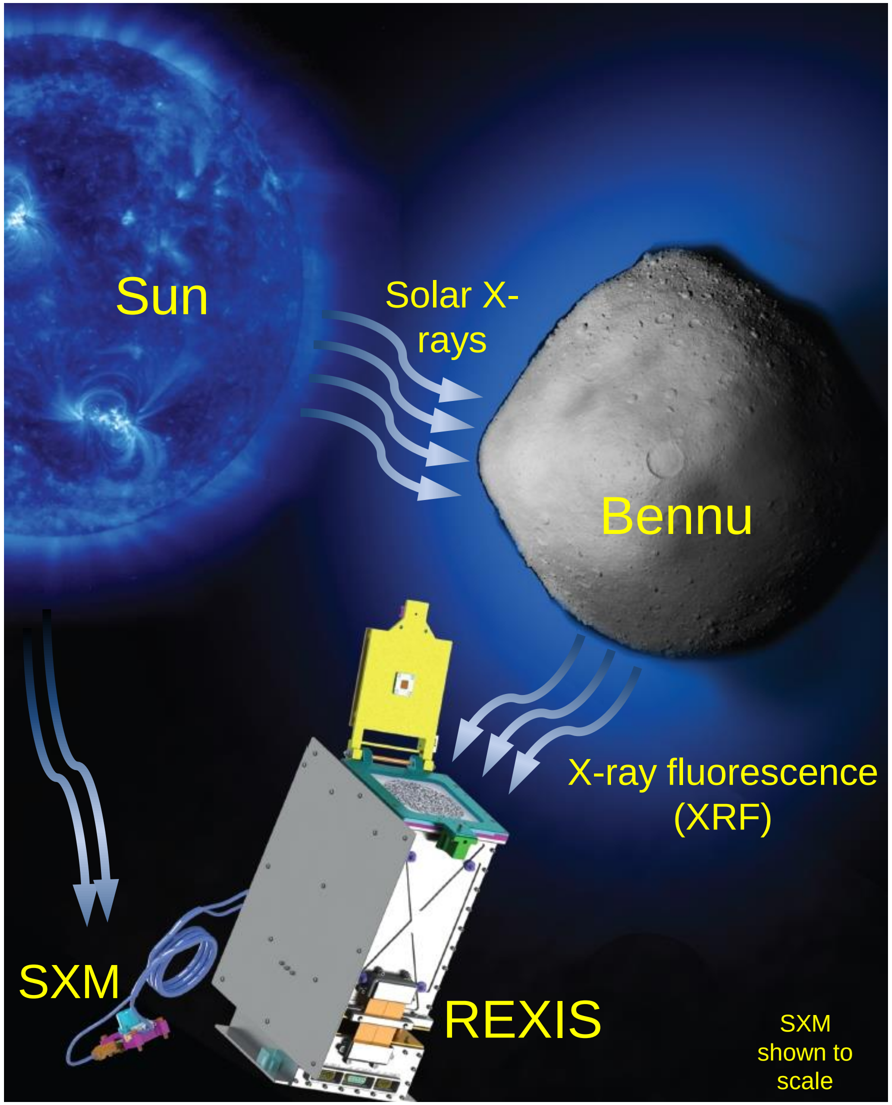
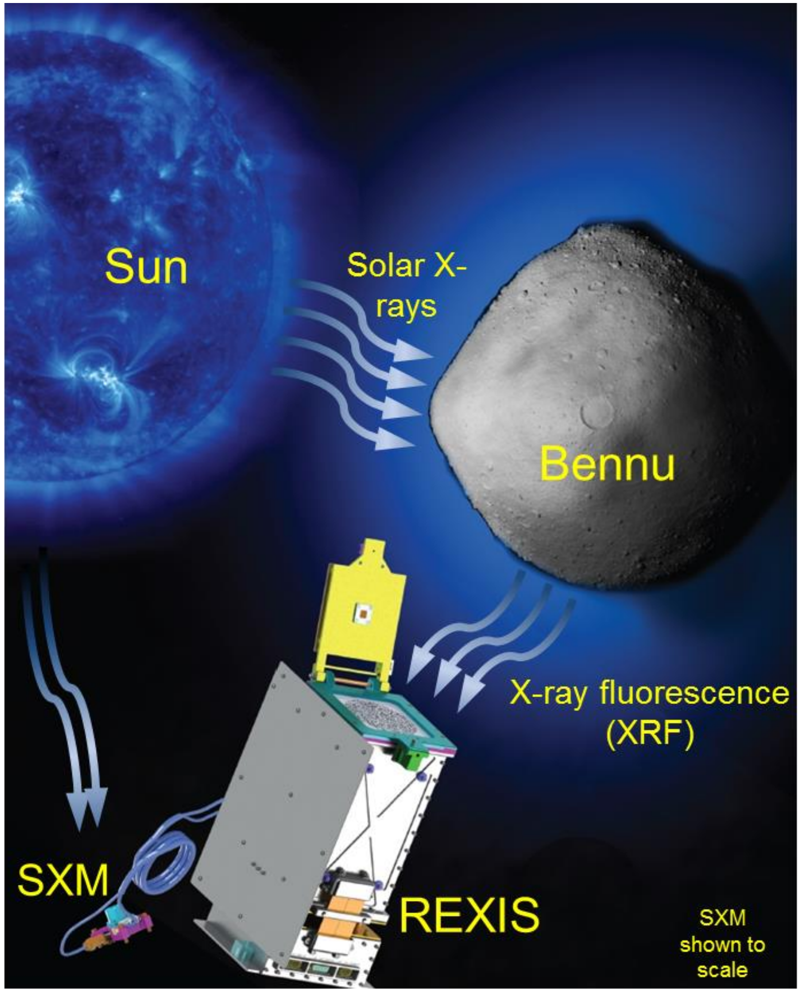
REXIS Science Goals

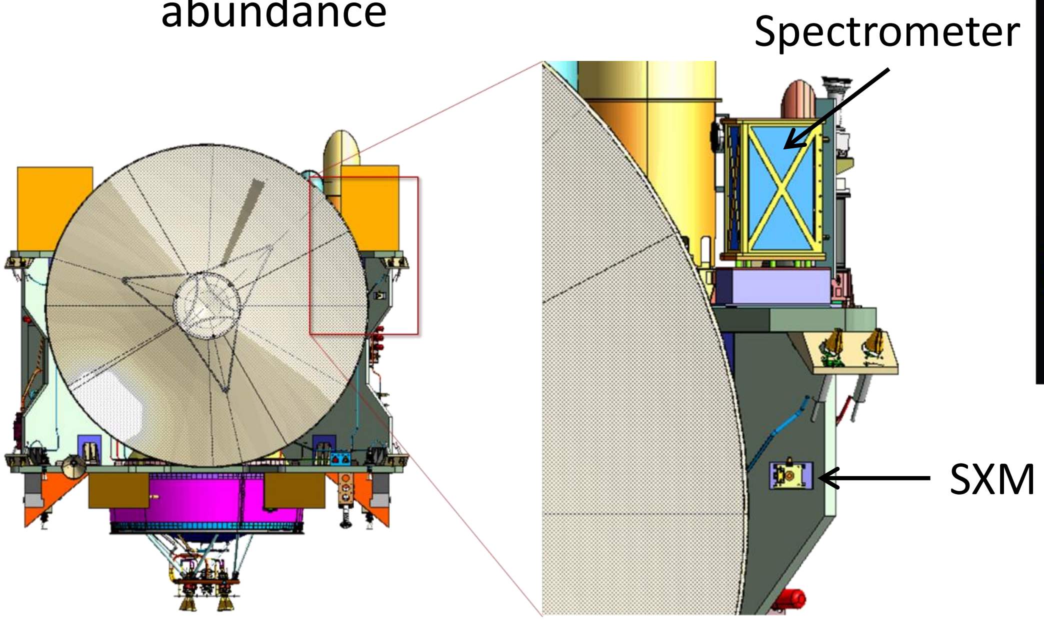
- X-ray fluorescence (XRF) of Bennu surface stimulated by incident solar X-rays
- Fluorescent line energies depend on the electronic structure of the matter
  - Provides a unique elemental signature
  - Line strengths reflect element abundance
- Photons are fluoresced from the surface of Bennu, some of which enter REXIS
- Concept heritage from NEAR, Hayabusa
- Imaging and detector heritage from astrophysics



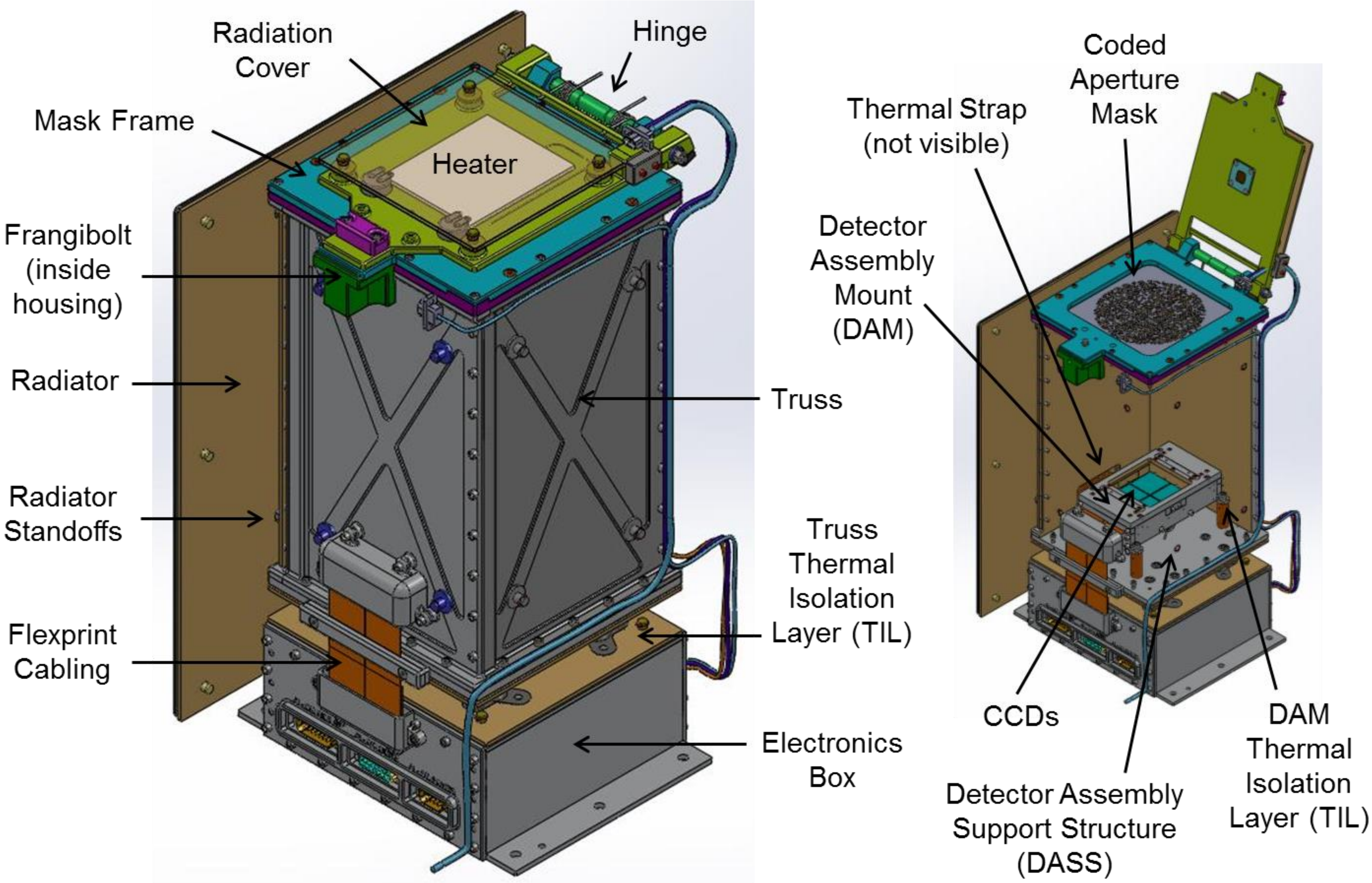
REXIS Science Goals

- One of five instrument on the OSIRIS-REx asteroid sample return mission scheduled for launch in 2016
- Measures X-rays that are fluoresced from Bennu
- Fluorescent line energies depend on the electronic structure of the matter
  - Provides a unique elemental signature
  - Line strengths reflect element abundance

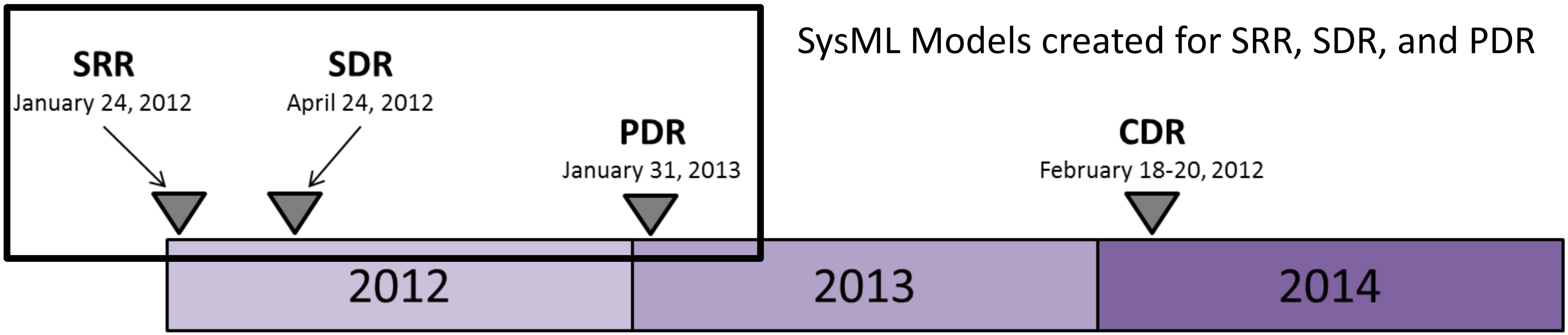




REXIS CDR Spectrometer Design

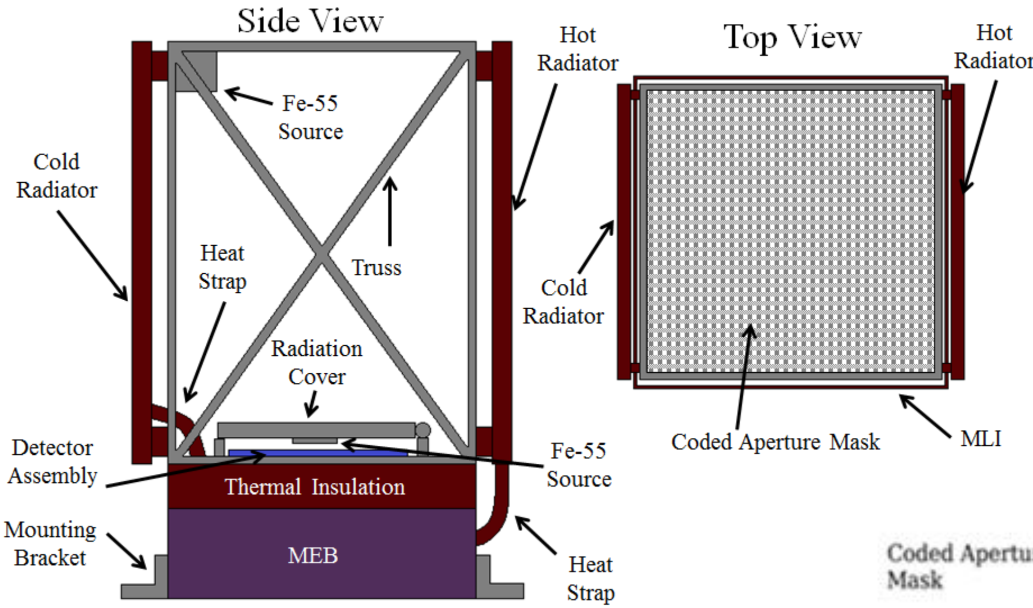


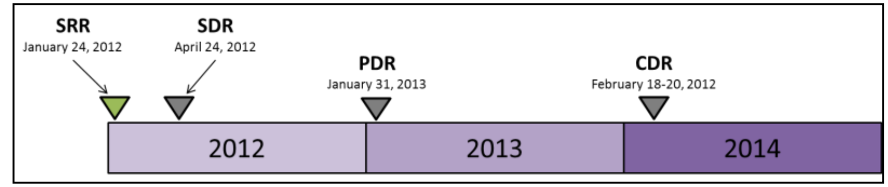
REXIS Design History Overview



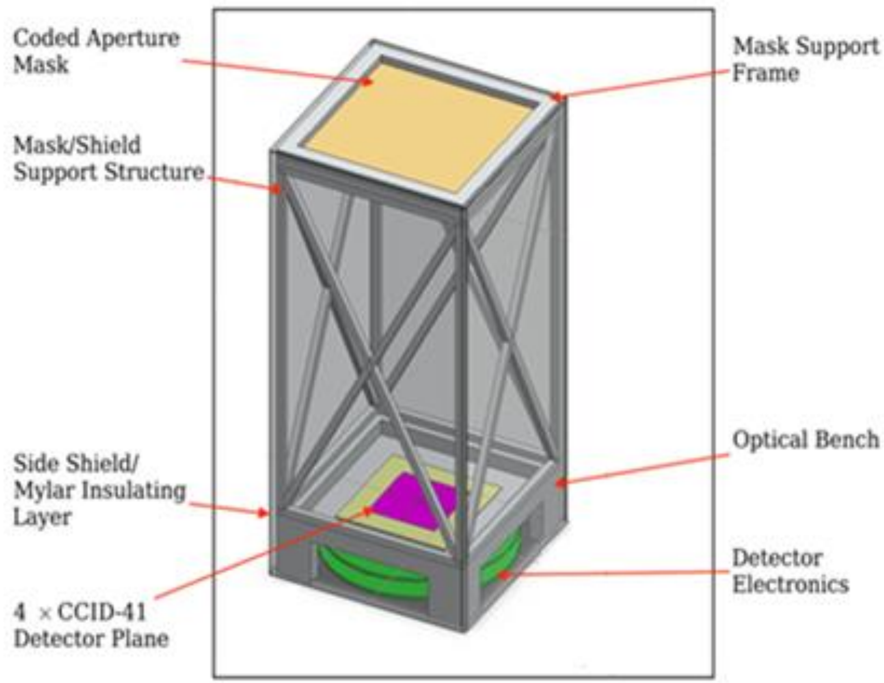
- SysML models created at SRR, SDR, and PDR
- From Fall 2011 through Spring 2012, REXIS team composed primarily of undergraduates
  - With grad students and faculty mentors
- From Summer 2012 to present, REXIS team composed primarily of grad students
  - With faculty mentors and undergraduate volunteers

REXIS SRR Design





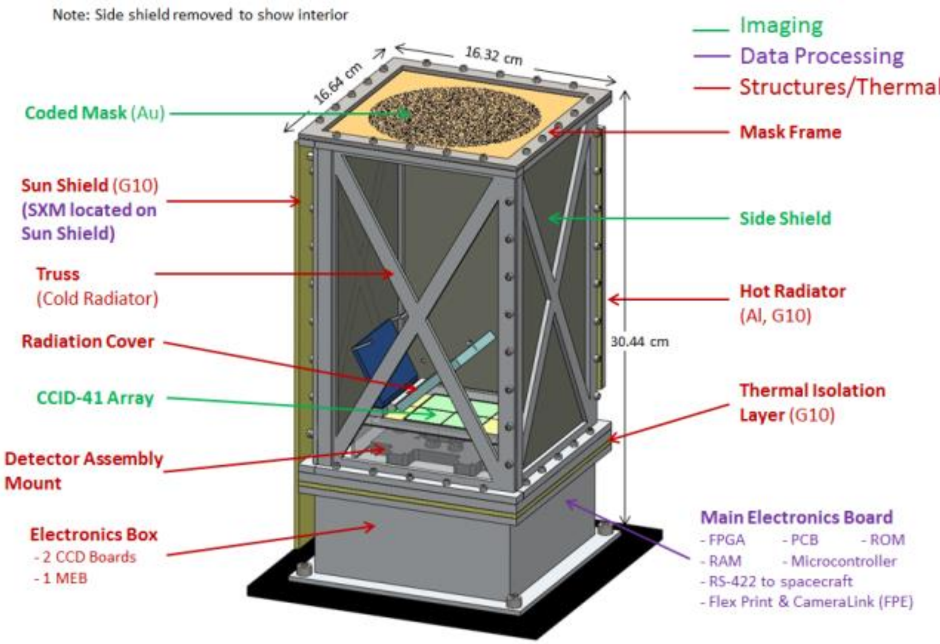
- SRR design largely reflects proposal design

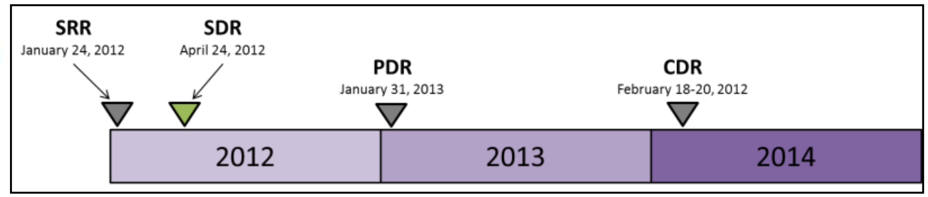


<u>Model Statistics</u>

- 28 parts
- 109 ports

REXIS SDR Design

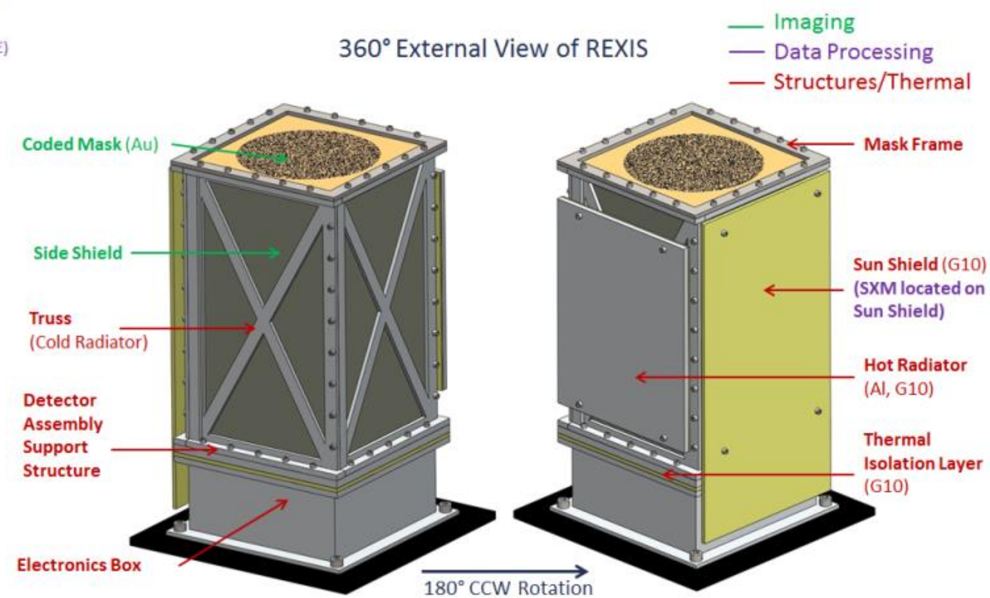




- Electronics Box coupled to S/C deck
- Removal of Cold Radiator
- Addition of Radiation Cover

<u>Model Statistics</u>

- 57 parts
- 210 ports

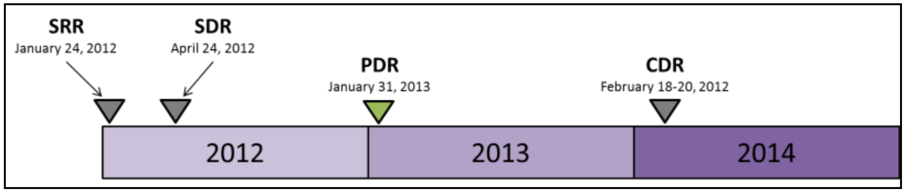


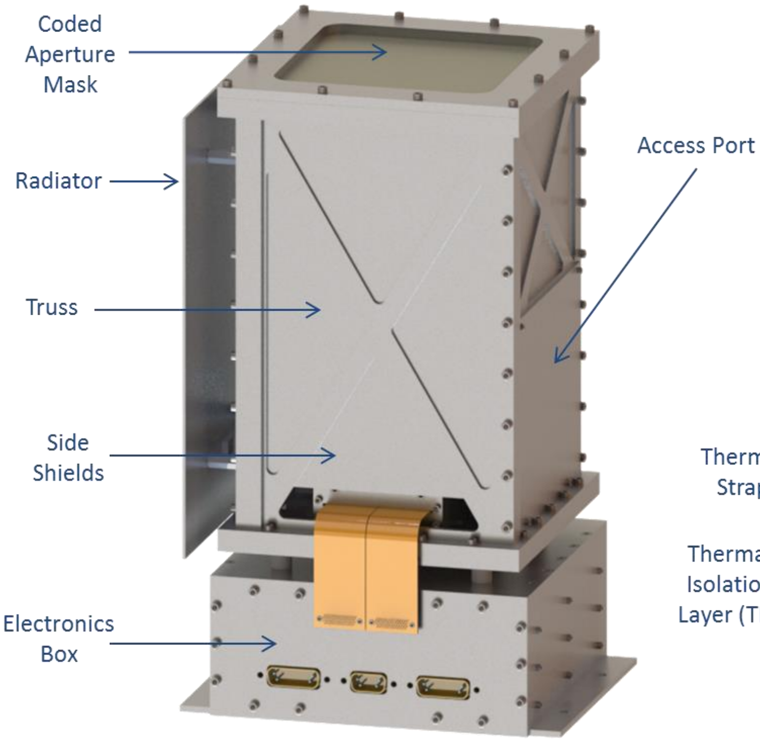
REXIS PDR Design

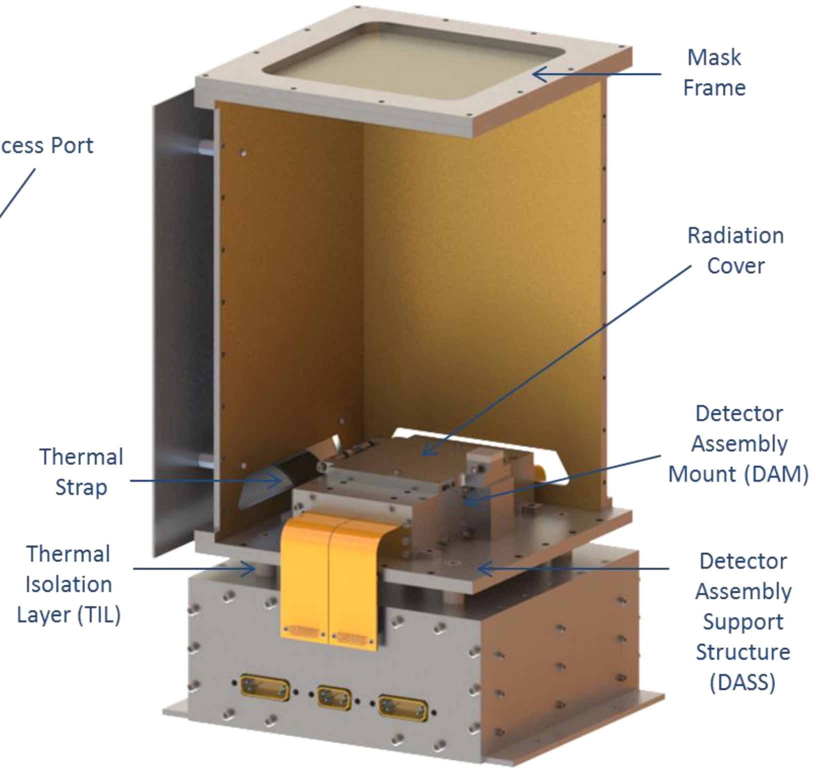
Model Statistics

- 150 parts
- 577 ports

- Removal of Hot Radiator
- Standoffs for thermal isolation

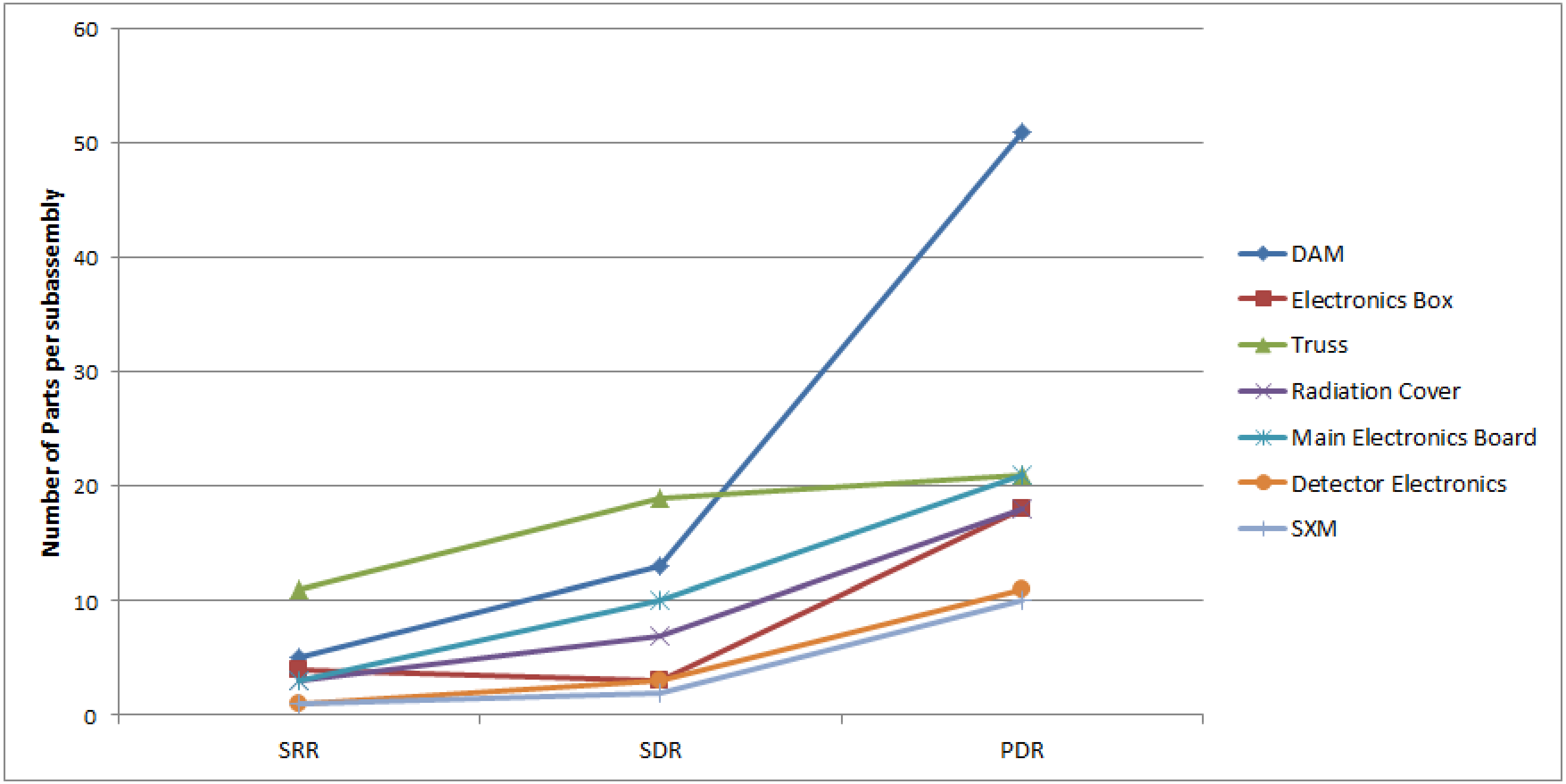






Design History Statistics

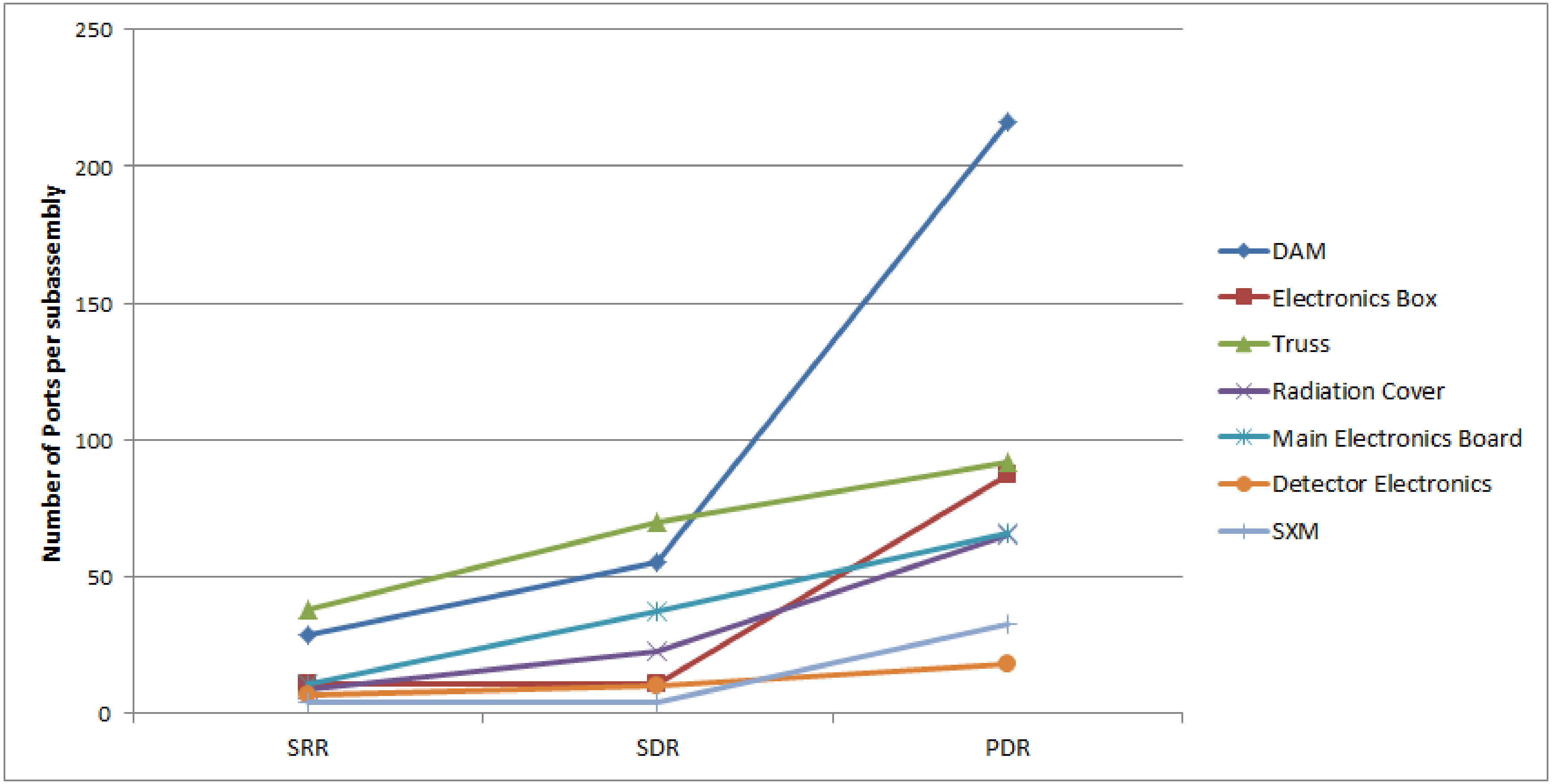
Parts per Assembly



All assemblies experienced parts growth

Design History Statistics

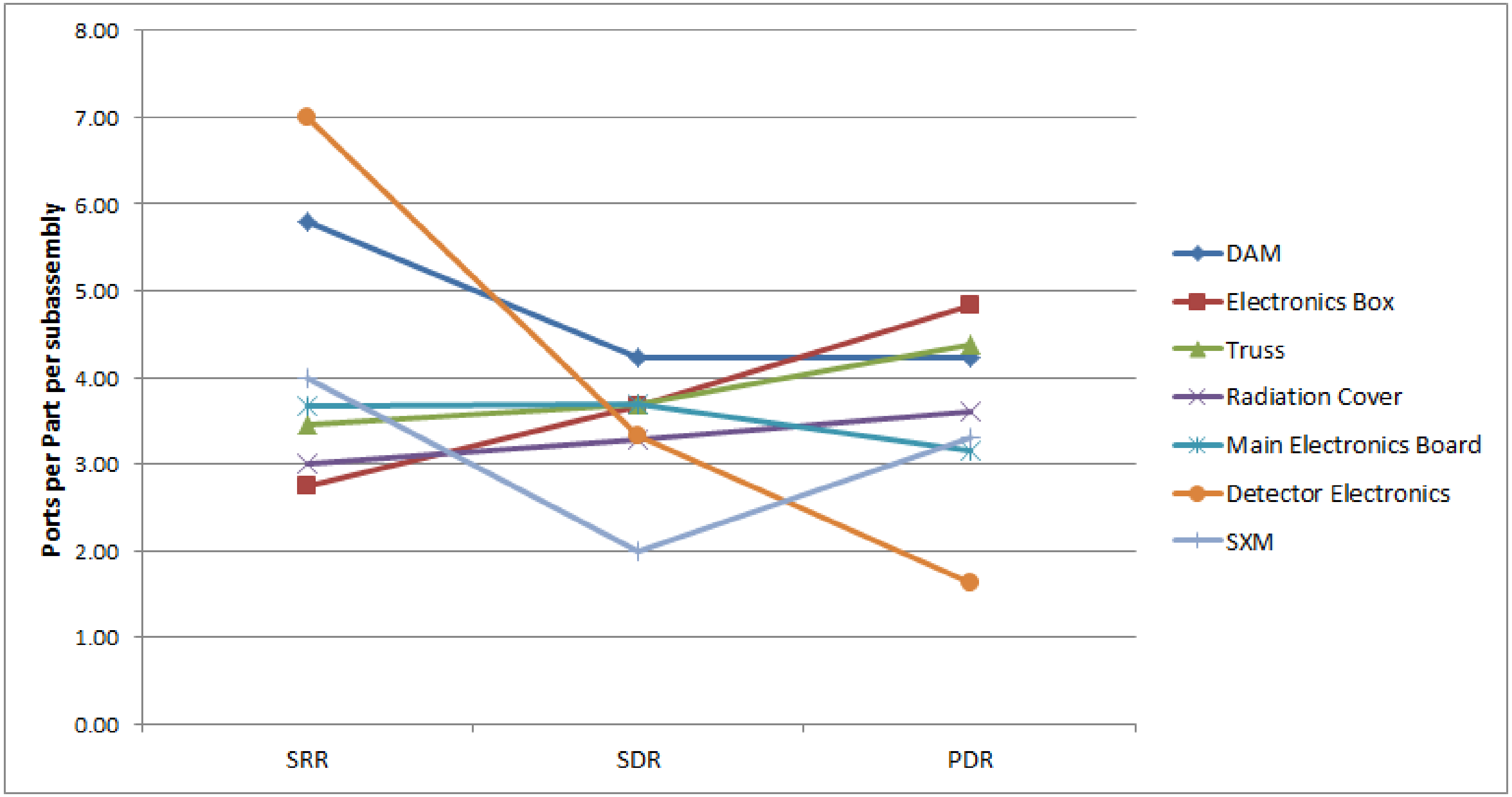
Ports per Assembly



All assemblies experienced interface growth

Design History Statistics

Ports Per Part in each Assembly



Agrees fairly well with previous research on the typical number of interfaces per part [9]

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Interface Uncertainty Case Study

- How well does interface uncertainty predict future growth or size of assemblies?

Create SysML models of design at points in design history

↓

Inspect models to extract information that is helpful to the design process

↓

Measure how the new information can improve the design process

<u>Case Study Methodology</u>

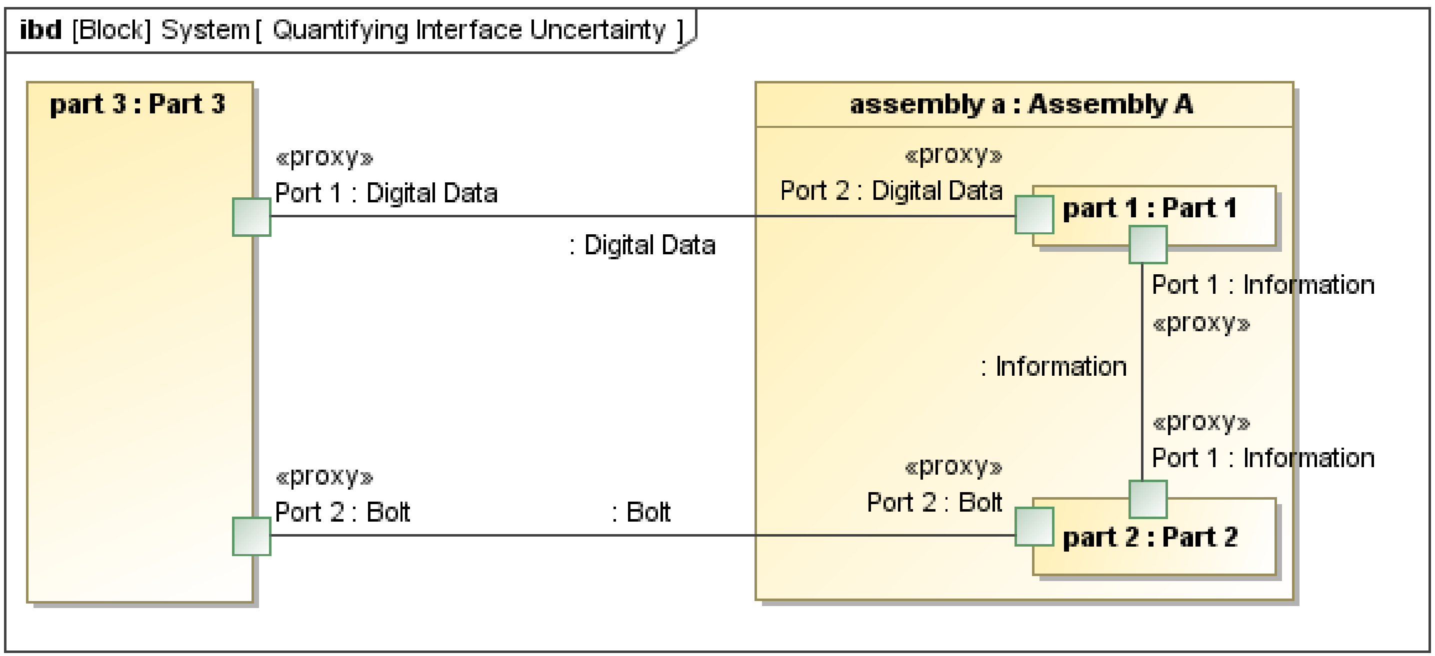
1. Incorporate interface uncertainty in REXIS SysML models
2. Quantify interface uncertainty in each REXIS assembly
3. Examine correlation of interface uncertainty to future assembly growth
4. Examine correlation of interface uncertainty and final assembly size

Quantifying Interface Uncertainty

Step 1: Modeling REXIS in SysML → **Step 2: Quantifying Interface Uncertainty** → Step 3: Predicting Assembly Growth → Step 4: Predicting Assembly Size

$$IU = \frac{1 - N_{LA}}{N_{LA}}$$

where:
IU = Interface Uncertainty
N_{LA} = Number of Interfaces at the Lowest Level of Abstraction
IU_A = Interface Uncertainty of Assembly A

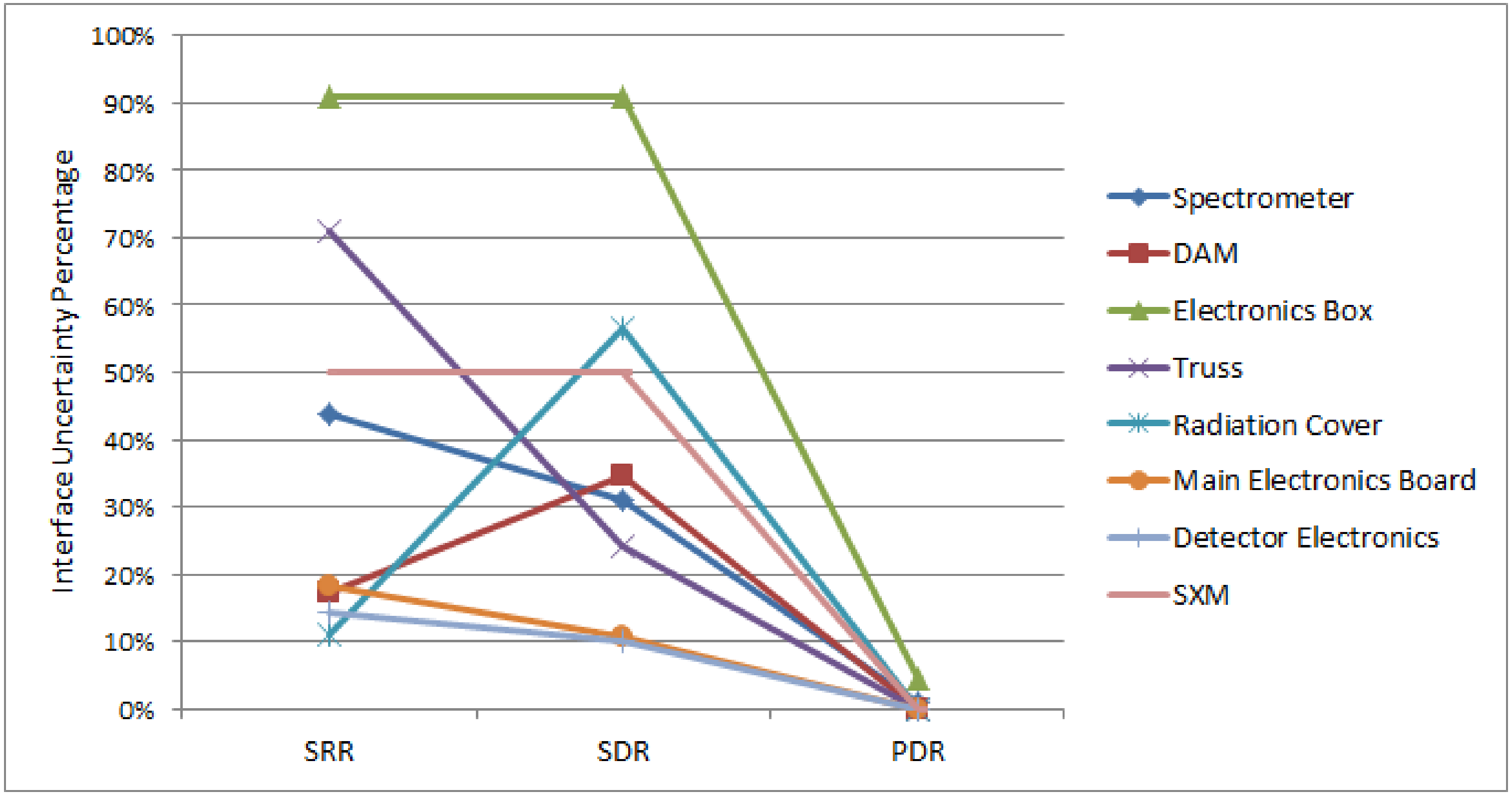


$$IU_A = \frac{1}{3}$$

Interface Uncertainty Over Time

Step 1: Modeling REXIS in SysML → **Step 2: Quantifying Interface Uncertainty** → Step 3: Predicting Assembly Growth → Step 4: Predicting Assembly Size

Ports Per Part in each Assembly over Time

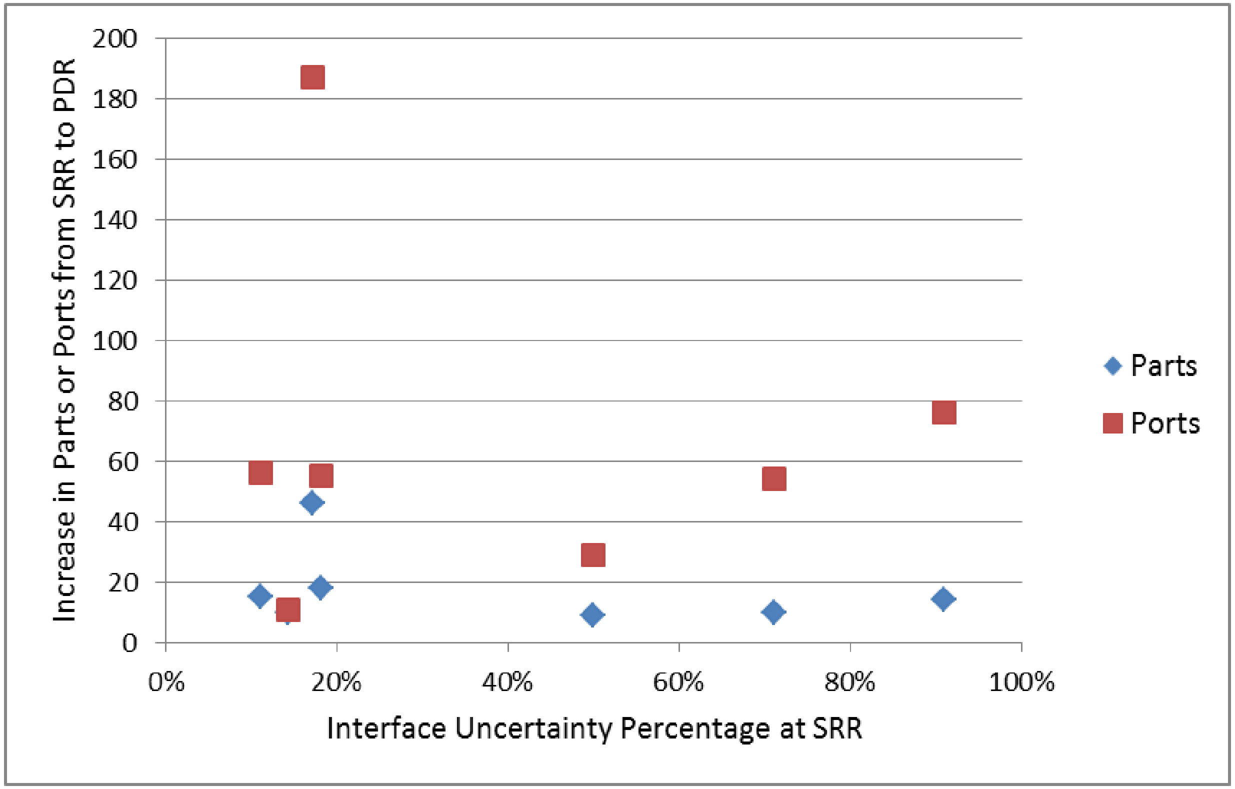


All assemblies experienced a decrease in uncertainty over time as expected

Predicting Assembly Growth

Step 1: Modeling REXIS in SysML → Step 2: Quantifying Interface Uncertainty → **Step 3: Predicting Assembly Growth** → Step 4: Predicting Assembly Size

Increase in Parts or Ports As Predicted By Interface Uncertainty at SRR

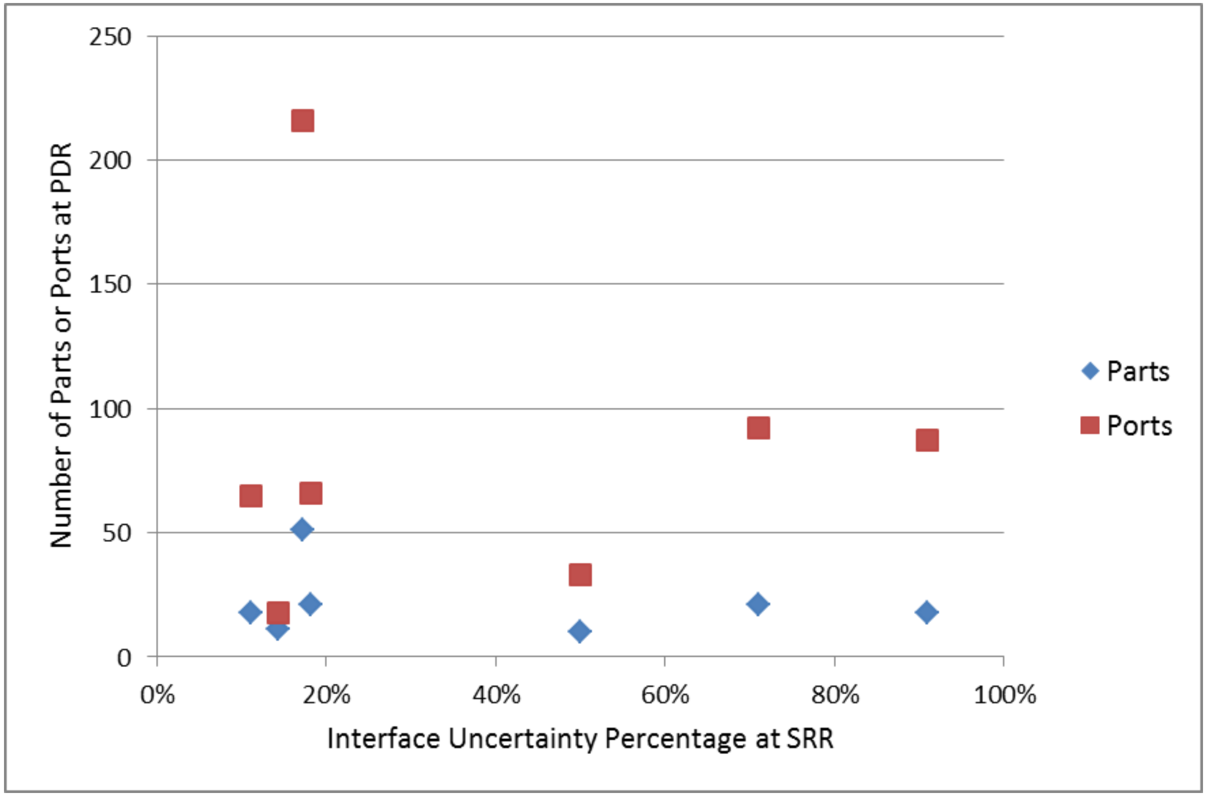


Interface uncertainty alone did not predict future increases in parts or ports

Predicting Assembly Size

Step 1: Modeling REXIS in SysML → Step 2: Quantifying Interface Uncertainty → Step 3: Predicting Assembly Growth → **Step 4: Predicting Assembly Size**

Total Assembly Size As Predicted By Interface Uncertainty at SRR



Interface uncertainty alone did not predict future size of an assembly

Case Study Conclusions

- Interface uncertainty alone unable to predict future assembly growth or final assembly size on REXIS
  - Some subassemblies did show expected trend but not where parts matured into multiple parts and interfaces
  - May work well as part of a more comprehensive metric that also captures part uncertainty
- With tweaks, interface uncertainty may be predictive
  - Using fraction of abstract interfaces to measure uncertainty unrealistically weights each interface evenly
  - Some interfaces evolved into many new parts and interfaces while other evolved into only a few parts or interfaces

Design Consequence Case Study

- Can tracing design consequence through the system improve decision making?

Create SysML models of design at points in design history

Inspect models to extract information that is helpful to the design process

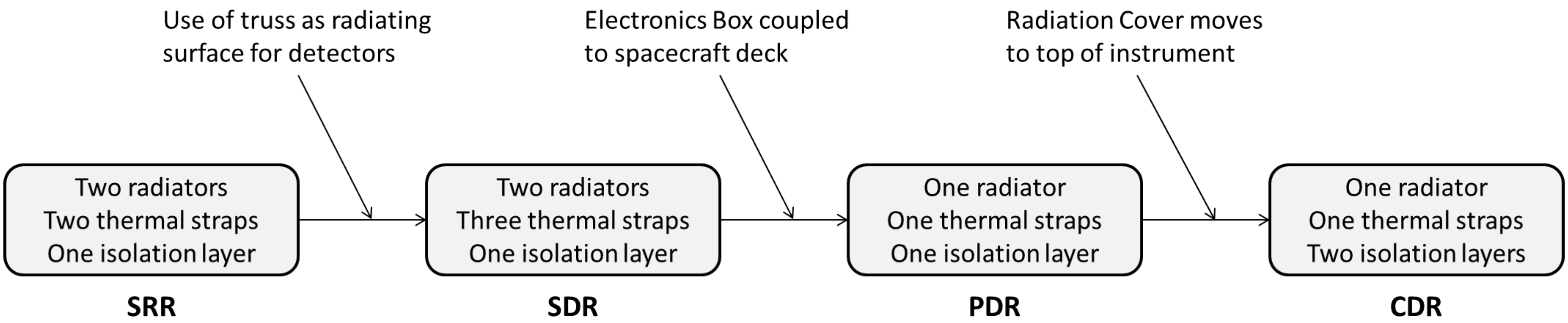
Measure how the new information can improve the design process

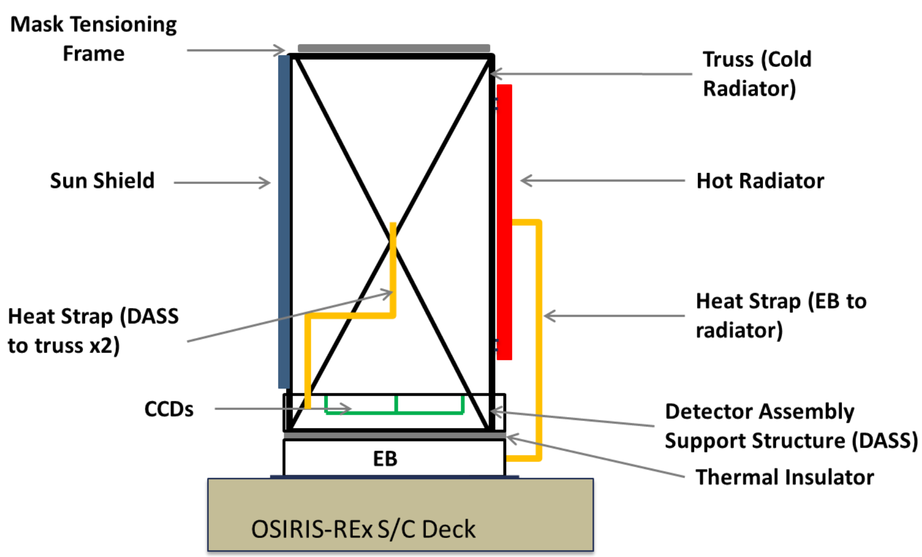
Case Study Methodology

1. Incorporate design consequences into REXIS SysML models
2. Inspect models to find design insights
3. Create alternative timeline based on information extracted from the model
4. Compare alternative timeline to historical timeline

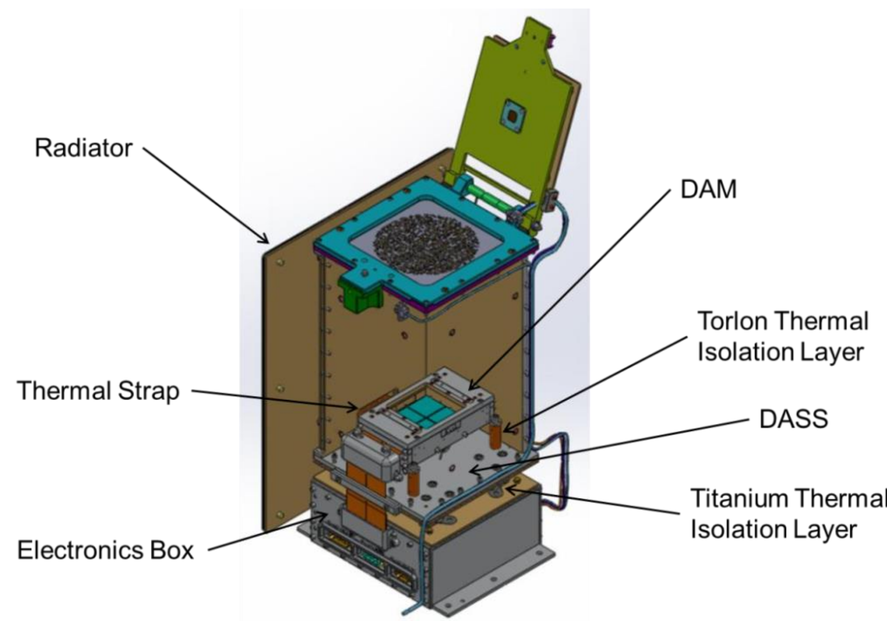
Thermal System Timeline

Historical Thermal System Timeline





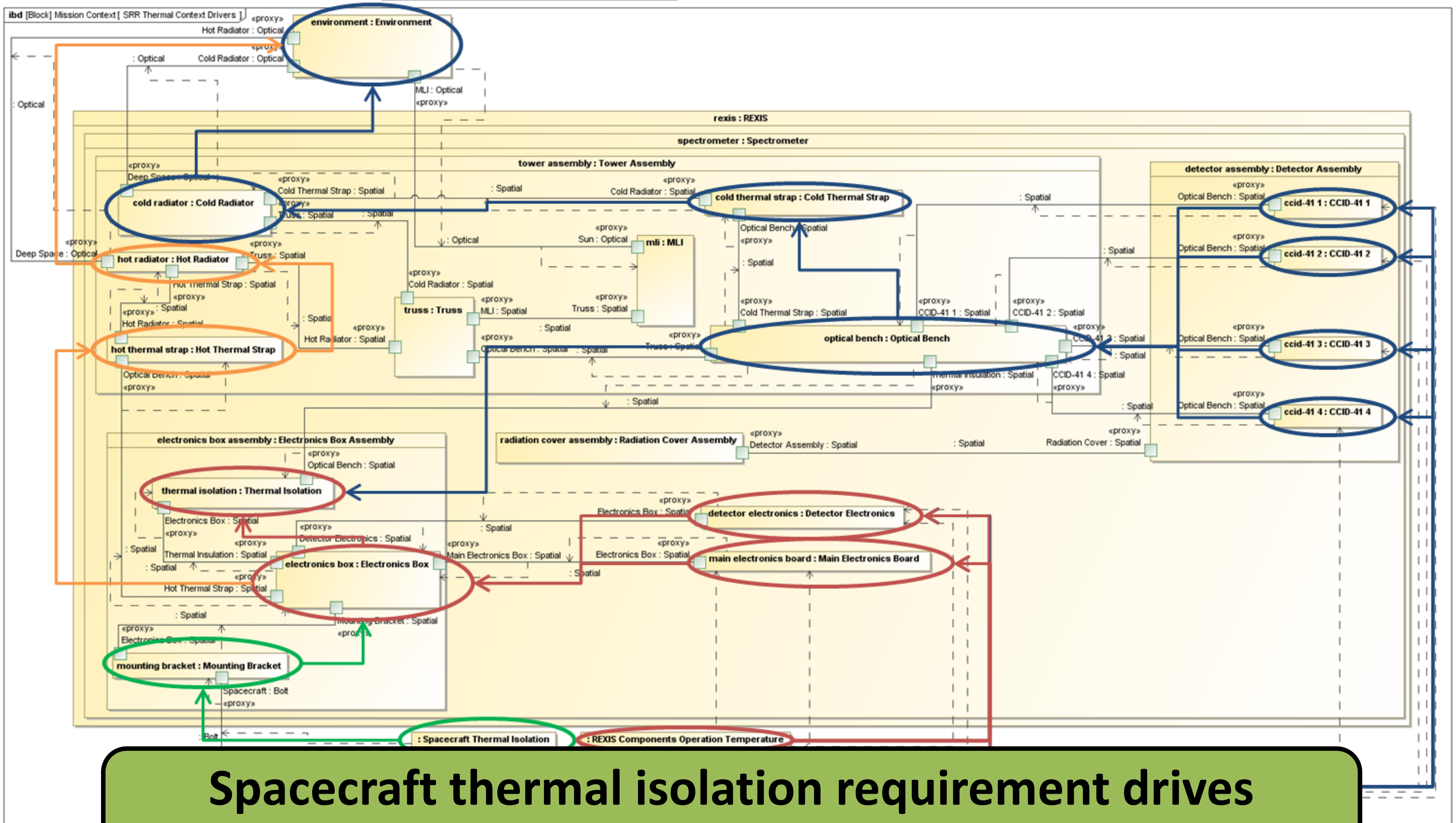
SDR Thermal Design



CDR Thermal Design

Inspecting the SRR Model

Step 1: Modeling REXIS in SysML → **Step 2: Inspecting the Model** → Step 3: Constructing Alternate Timeline → Step 4: Comparing Timelines

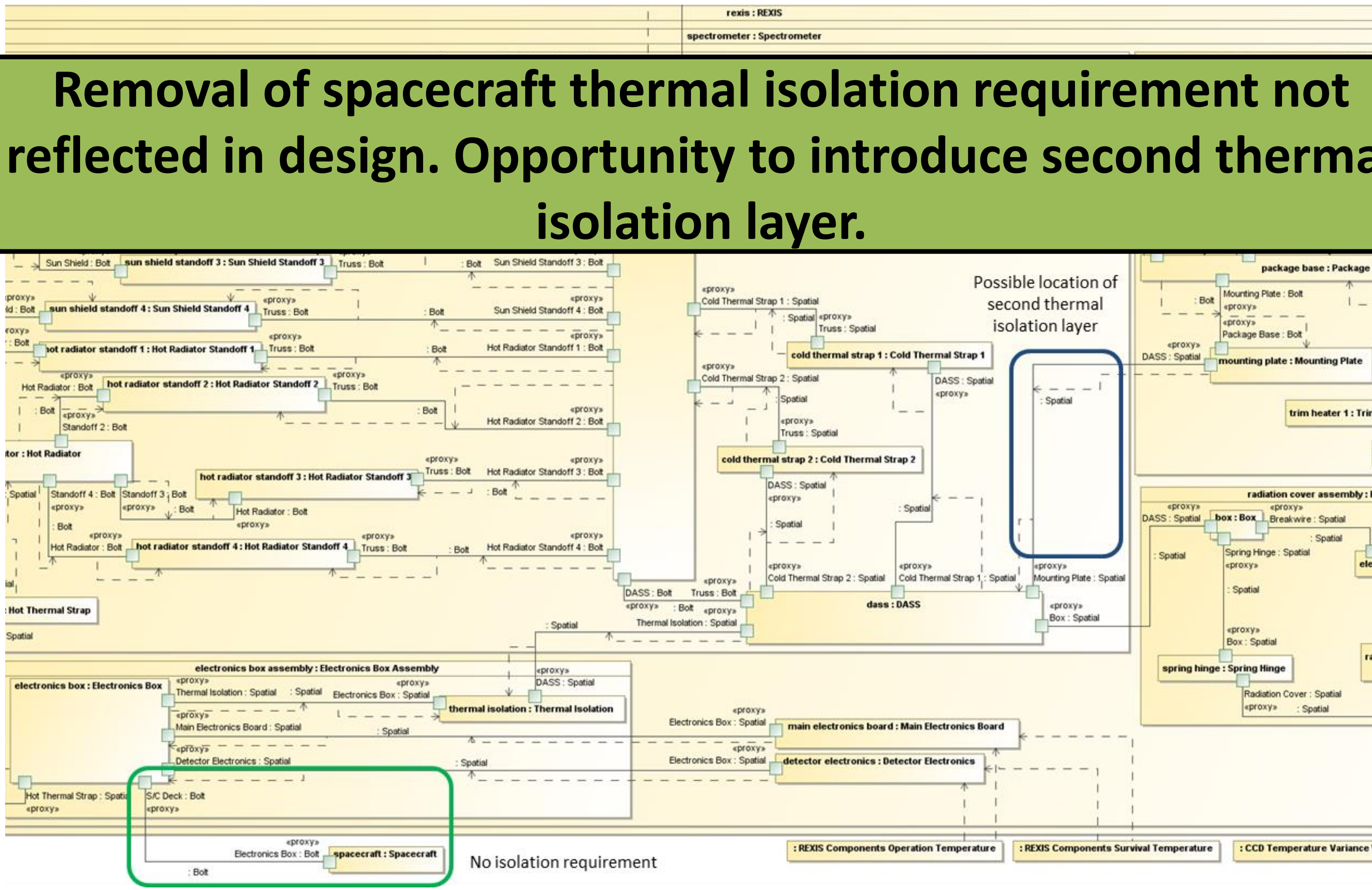


Spacecraft thermal isolation requirement drives second radiator

Inspecting the SDR Model

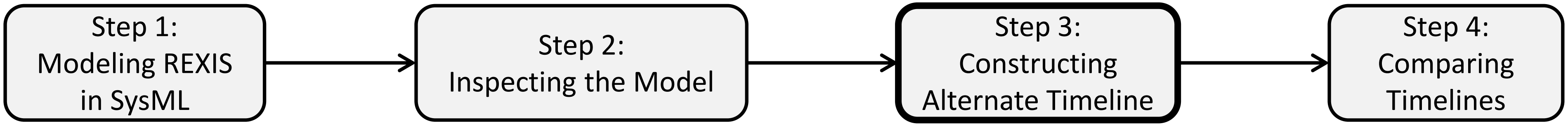
Step 1: Modeling REXIS in SysML → **Step 2: Inspecting the Model** → Step 3: Constructing Alternate Timeline → Step 4: Comparing Timelines

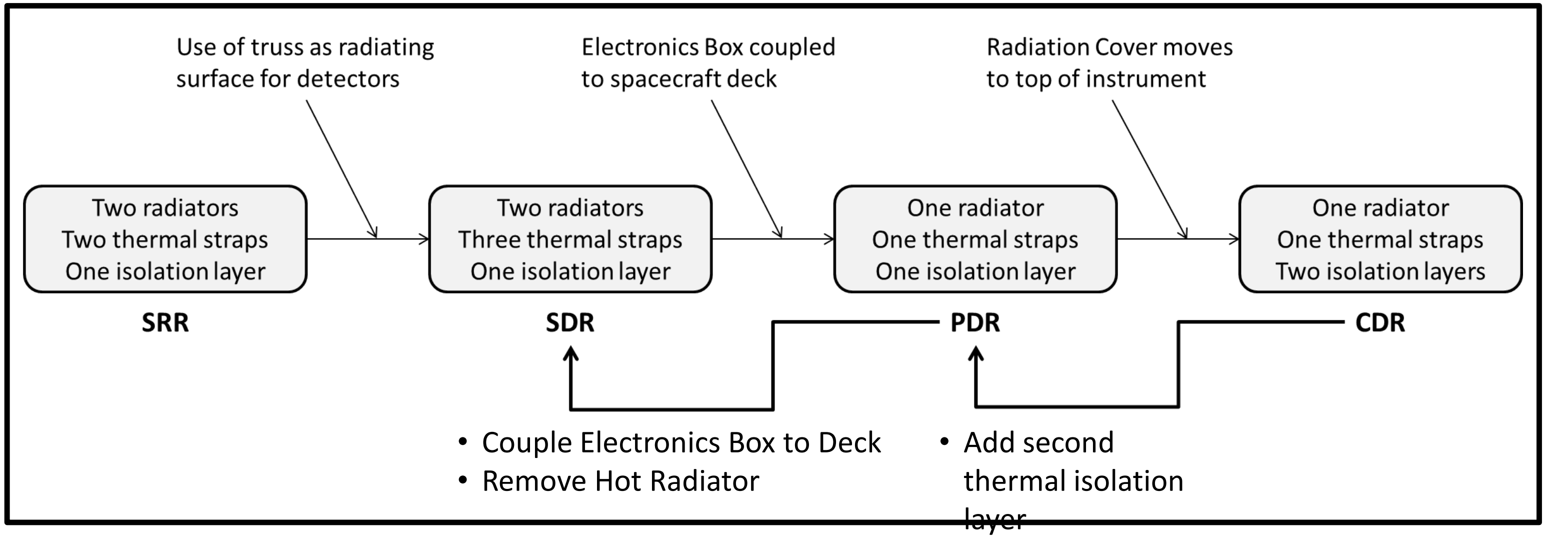
Removal of spacecraft thermal isolation requirement not reflected in design. Opportunity to introduce second thermal isolation layer.

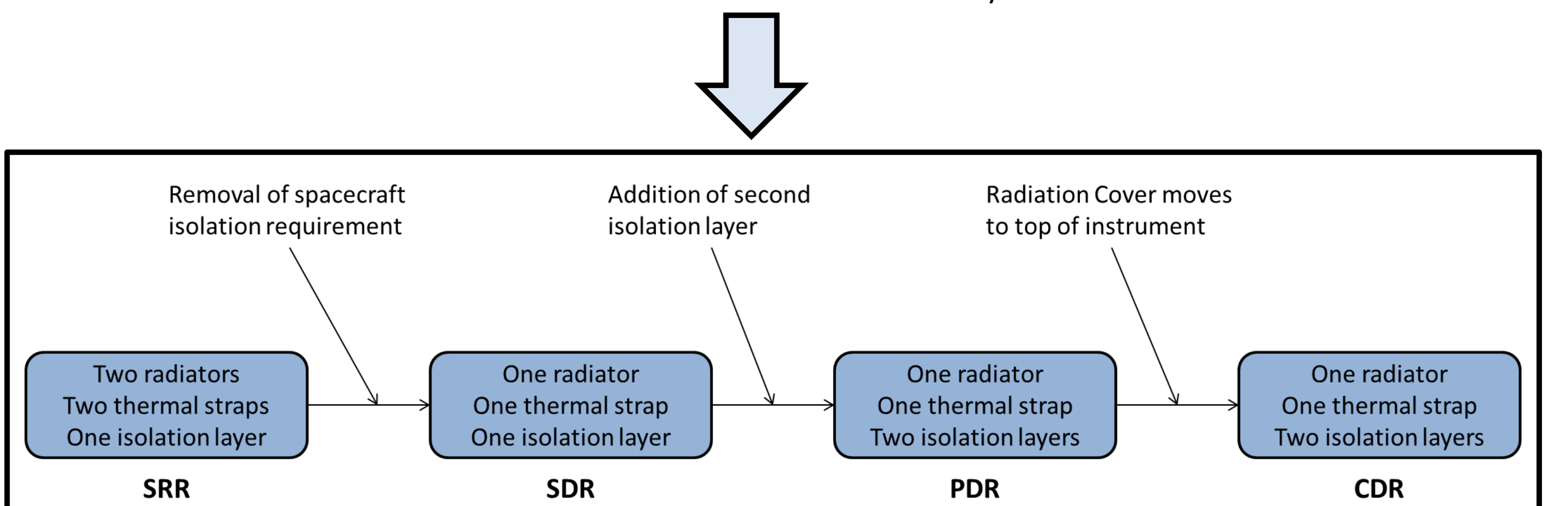


SysML model of Thermal System Design at SDR

Constructing Alternate Timeline







Comparing Timelines

Step 1: Modeling REXIS in SysML → Step 2: Inspecting the Model → Step 3: Constructing Alternate Timeline → **Step 4: Comparing Timelines**

Historical Thermal Design Timeline

SRR: Two radiators, Two thermal straps, One isolation layer

→ Use of truss as radiating surface for detectors →

SDR: Two radiators, Three thermal straps, One isolation layer

→ Electronics Box coupled to spacecraft deck →

PDR: One radiator, One thermal straps, One isolation layer

→ Radiation Cover moves to top of instrument →

CDR: One radiator, One thermal straps, Two isolation layers

Model-Based Design Timeline

SRR: Two radiators, Two thermal straps, One isolation layer

→ Removal of spacecraft isolation requirement →

SDR: One radiator, One thermal strap, One isolation layer

→ Addition of second isolation layer →

PDR: One radiator, One thermal strap, Two isolation layers

→ Radiation Cover moves to top of instrument →

CDR: One radiator, One thermal strap, Two isolation layers

Model-based design timeline is more efficient than historical design timeline

Case Study Conclusions

- Design consequence tracing revealed information about the REXIS design before it was known historically
- Information extracted from the system models reduced design iteration and rework

Modeling design consequences on REXIS provides the opportunity to make the design process more efficient

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Summary and Conclusions

- Thesis investigated how model-based systems engineering can improve the design process
- System models captured topological information
  - Interfaces, interface uncertainty, and design consequences
- Interface uncertainty not a good predictor of future REXIS assembly growth or final size
- Design consequence tracing highlighted important REXIS design information

Implementation of MBSE on REXIS would have improved the design process

Thank You!

Questions?

Bibliography

[1] D.L. Emmons, M. Lobbia, T. Radcliffe, and R.E. Bitten. Affordability Assessments to Support Strategic Planning and Decisions at NASA. In Aerospace Conference, 2010 IEEE, 2010.

[2] D.A. Bearden. A complexity-based risk assessment of low-cost planetary missions: when is a mission too fast and too cheap? Acta Astronautica, 52(26):371 - 379, 2003.

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